A Commentary on Nils Aall Barricelli's "*Esempi Numerici di Processi di Evoluzione*" (1954)*

Tim Taylor[1,2], Giulia Bianchi[3]

Corresponding author: Tim Taylor (tim@tim-taylor.com)

1. Department of Data Science and AI, Monash University, Australia
2. Independent Researcher, Edinburgh, United Kingdom
3. Freelance Translator, Vienna, Austria

Abstract. The Italian-Norwegian scientist Nils Aall Barricelli conducted pioneering work on the evolution of digital organisms in the 1950s and 1960s. His paper *Esempi Numerici di Processi di Evoluzione* (Numerical Examples of Evolutionary Processes), published in the Italian journal *Methodos* in 1954, is, to the best of our knowledge, the first publication describing experiments in computational evolution and artificial life. Had the paper been more widely known when the field of Artificial Life coalesced as a recognised discipline in the 1980s, there is little doubt that it would have greatly influenced early research directions and established Barricelli as a founding father of the discipline. However, despite the historical significance of the paper, it has until now remained a fairly obscure publication—*Methodos* ceased publication in 1964, and copies of the paper are hard to find online. In publishing an English translation of the paper in this issue of the *Artificial Life* journal, we aim to provide a much more widely accessible version of the work. In this accompanying commentary, we provide some scientific and biographical context for the paper, discuss how it relates to Barricelli's earlier and later publications, comment on the process of translating the work and issues that arose in the process of doing so, and reflect on the legacy and significance of the work today.

Keywords: Nils Aall Barricelli, history of artificial life, computational evolution, digital organisms, symbiogenesis, open-ended evolution

*This is an author-formatted version of a paper published in the *Artificial Life* journal. Please cite the published version as follows: Taylor, T., & Bianchi, G. (2026). *A commentary on Nils Aall Barricelli's "Esempi numerici di processi di evoluzione" (1954)*. Artificial Life, 32(3), 318–343. https://doi.org/10.1162/ARTL.a.488.

1 Introduction

In this issue of the *Artificial Life* journal we present an English translation of the paper *Esempi Numerici di Processi di Evoluzione* (Numerical Examples of Evolutionary Processes) by the Italian-Norwegian scientist Nils Aall Barricelli (Barricelli et al., 2026). The original Italian version of the paper was published in 1954 in the journal *Methodos*, a publication of the *Centro Italiano di Metodologia e Analisi del Linguaggio* (Italian Center for Methodology and Analysis of Language) in Milan (Barricelli, 1954). The first page of the original publication is reproduced in Figure 1.

The paper reports the results of Barricelli's early simulations of evolutionary processes. Most of these had been manually calculated by Barricelli himself, but towards the end of the paper he describes much larger-scale experiments conducted on an early electronic computer developed by John von Neumann's Electronic Computer Project at the Institute for Advanced Study (IAS) in Princeton, NJ. These experiments had been conducted in 1953 during the first of three research visits made by Barricelli to von Neumann's group at IAS. The paper therefore documents the transition from paper-and-pen simulations to the very first evolutionary simulations performed on computers.

Our purpose in writing this commentary is as follows: to provide some details of the context in which the original paper was written; to discuss the contents of the paper and how it relates to Barricelli's earlier and later works; to provide details of the translation processes and some errors we found in the original paper; and, finally, to offer some remarks on the significance and legacy of the paper.

2 Personal and scientific background and context

Nils Aall Barricelli was born in Rome in 1912, son of Italian artist Maurizio Barricelli and Norwegian author and women's rights activist Maren Anna Nielsine (Marna) Aall. He spent some of his childhood in Norway but studied mathematics and physical sciences at the University of Rome under Enrico Fermi, graduating in 1936. Prompted by the rise of the National Fascist Party in Italy, he relocated back to Norway later that year.

In the years between returning to Norway and his first visit to IAS in 1953, Barricelli pursued a variety of research interests at the University of Oslo, where he also lectured. Always an independent thinker, his research covered topics such as theoretical statistics and stationary time series, tensor calculus and relativity theory, and the mathematical theory of evolution. He first investigated the latter over the period 1945–1948 and returned to the topic in 1951.[1]

[1]This information was stated by Barricelli on an application for a US Government Travel grant in 1951 (Barricelli, n.d.-a, p.11).

ESEMPI NUMERICI DI PROCESSI DI EVOLUZIONE

NILS AALL BARRICELLI

Institute for Advanced Study
Princeton, N. J.
U. S. A.

(Ricevuto il 30 dicembre 1953)

1. Il problema dell'origine degli organismi viventi.

Man mano che la scienza ci ha messi in grado di comprendere ed interpretare una parte sempre maggiore dei fenomeni naturali, le questioni ancora insolute hanno assunto un interesse sempre maggiore per gli studiosi di tutti i paesi. Una di queste questioni che maggiormente han destato la curiosità degli nomini può essere posta nei termini seguenti:

« Come mai esistono organismi viventi? »

Un contributo fondamentale alla soluzione di questa questione fu quello apportato da Darwin. Anche se le indagini successive hanno portato a modificare i concetti di Darwin sul modo in cui avvengono i cambiamenti ereditari, resta fermo il fatto fondamentale scoperto da Darwin che le specie si evolvono per cambiamenti ereditari e selezione naturale. Gli organismi più vitali, più adatti all'ambiente sopravvivono. Ne deriva che i cambiamenti ereditari più vantaggiosi per gli individui si diffondono mentre i più nocivi scompaiono. Le specie hanno in tal modo la possibilità di evolversi verso una sempre maggiore perfezione, acquistando organi e caratteri che le rendono sempre più adatte alla vita ed alla concorrenza con le altre specie.

Questa teoria non risponde alla nostra domanda, non ci dice perché esistono gli organismi viventi; ma tenta di rispondere ad una altra domanda che a questo riguardo non è senza importanza e cioé: « Perché gli organismi viventi sono talmente complessi, perché sono forniti di organi e facoltà così efficaci e perfetti, così utili alla vita degli organismi stessi? ».

Figure 1: The first page of Barricelli's *Esempi Numerici* paper as it appeared in the *Methodos* journal in 1954.

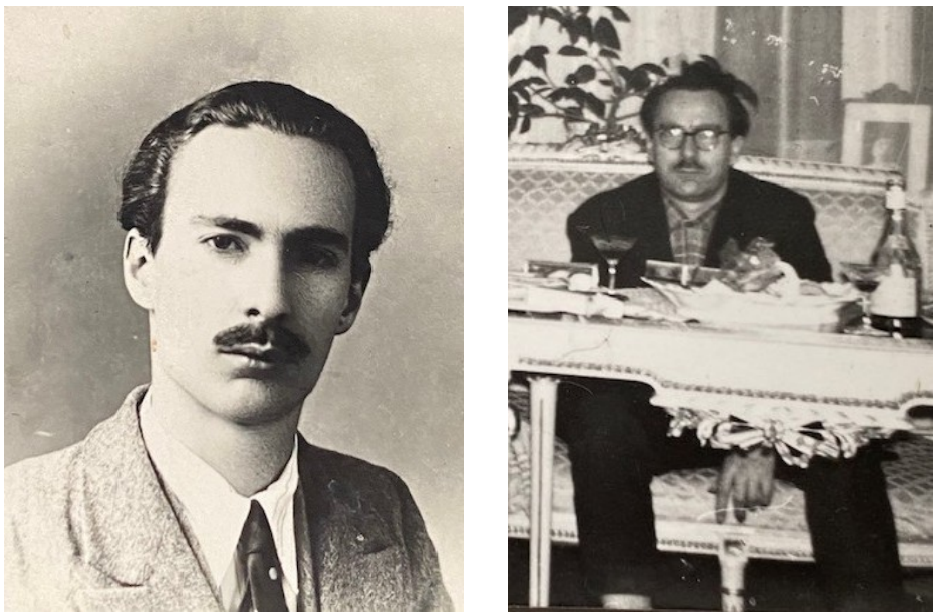


Figure 2: Photographs of Nils Aall Barricelli as a young man (left) and in middle age (right) courtesy of his nephew Cato Brahde. Reproduced with permission.

2.1 Interest in Kozo-Polyansky's theory of symbiogenesis

From his earliest investigations in evolutionary theory, Barricelli had been interested in the role of symbiosis in evolutionary processes, and in particular in its role in the origin of gamic (sexual) reproduction. He was inspired by the work of the Russian biologist Boris Kozo-Polyansky, who, in 1924, had published *Novyi printzip biologii. Ocherk teorii simbiogeneza* (The New Principle of Biology. Essay on the Theory of Symbiogenesis) (Kozo-Polyansky, 1924). This in itself marks out Barricelli as a somewhat unusual character, since Kozo-Polyansky's book, in Russian, was largely unknown by scientists in the West at the time. The recognition of the idea of symbiogenesis by Western scientists had to wait for the contributions of Lynn Margulis, whose work on the topic became increasingly accepted over the period from the mid-1960s to the 1980s. And Kozo-Polyansky's contributions only became widely known in the West in 2010 when Victor Fet and Margulis published an English translation of his book (Kozo-Polyansky, 2010).

Kozo-Polyansky argued that eukaryotic cells, and the organelles within them, had emerged through the symbiosis of simpler organisms. His argument encompassed even the chromosomes within the cell: "each chromosome is a colony or consortium, i.e. an individual of a higher order, physiologically indivisible, and from the genetic viewpoint representing a system of individuals of lower order" (Kozo-Polyansky, 2010, p.38). On the implications of his theory of symbiogenesis for our understanding of evolution, Kozo-Polyansky suggested that "[i]n this principle of internal, endosomatic, and intracellular struggle, biology can possibly find a key to understanding the causes of mutations and other hereditary phenomena." (Kozo-Polyansky, 2010, p.115).

2.2 Initial development of numerical models of evolution and symbiogenesis

Barricelli took Kozo-Polyansky's idea to heart. In a research report published in 1947, he employed theoretical and mathematical arguments, based upon the work of Fisher (1930) and Haldane (1924), to explore the conditions under which "gene-symbiosis" (the symbiotic pairing of formerly independent genes) might be advantageous (Barricelli, 1947). While he continued to develop mathematical models of evolutionary processes throughout his career, by 1951 he had also started to develop a very different kind of approach involving "numerical models". These were somewhat similar to what we would now call one-dimensional cellular automata, involving a row of discrete locations, each of which could either be empty or contain a positive or negative integer.[2] This simple "universe" was updated in discrete time steps, with a set of rules determining the new state of each location based upon the previous state of the universe. Throughout 1951 Barricelli "absorbed himself in the construction of [these] 'numerical models'"[3] and spent much of his time experimenting with update rules that would allow numbers to "reproduce" (make additional copies of themselves) either by themselves or with the "symbiotic" assistance of neighbouring numbers.

Barricelli's early explorations of the dynamics of these numerical models were calculated by hand using paper and pen. As the size and complexity of his models increased, he performed heroic feats of perseverance in this process; the largest manually-calculated model reported in the 1954 paper featured a world size of 83 locations, iterated for 100 generations. To update each location at each generation, he had to consider potential interactions from several other locations. And he had to do this 8,300 times to complete the whole experiment![4] In order to develop these studies further, it was clear to Barricelli that he would need to find a way of automating these calculations.

2.3 Application to work at the Institute for Advanced Study (IAS) in Princeton

By the time Barricelli was performing these experiments in 1951, the University of Oslo had already started building Norway's first digital computer, named NUSSE (Norsk Universell Siffermaskin, Sekvensstyrt, Elektronisk) (Berntsen, 2003). However, this was a long-term project that would not be completed until 1954. In 1951 there were only a handful of operational digital computers in the world. One of the newest and most advanced of these was the "IAS Machine" being developed in von Neumann's Electronic Computer Project at the Institute for Advanced Study in Princeton; this machine became partially operational that year and fully operational in 1952.

Barricelli had a useful friend in Oslo who was able to write directly to von Neumann and

[2] In some configurations a location might also contain an "x" symbol.

[3] This quote is from a reference to support Barricelli's application to work at IAS, written by Ingebrigt Johansson, a professor of mathematics in Oslo, on 7 December 1951 (Barricelli, n.d.-a, p.17).

[4] Barricelli did sometimes have students working with him in Oslo, but he does not mention whether he received any help in performing these calculations.

introduce Barricelli's work to him: the economics professor (and, later, Nobel laureate) Ragnar Frisch. Frisch had co-founded the Econometric Society in 1930, and was editor of the journal *Econometrica* (Tinbergen, 1974). Given von Neumann's significant contributions to mathematical theories of economics with his colleague Oskar Morgenstern (von Neumann & Morgenstern, 1944), and the fact that von Neumann had been elected a fellow of the Econometric Society in 1947 (The Econometric Society, n.d.), he would undoubtedly have been aware of Ragnar and his work.

Frisch's letter of introduction met with an enthusiastic response from von Neumann, and Barricelli began applying for grants to fund the trip. In his application for a Fulbright travel grant, he stated that the purpose of his visit was "to perform numerical experiments by means of great calculating machines. The experiments are of interest in the mathematical theory of evolution and aim at clarifying the first stages in the evolution of species" (Barricelli, n.d.-a, p.15).

In a letter from von Neumann to Frisch dated 10 December 1951, he writes "I need not tell you that I am interested in reading Mr. Barricelli's more detailed papers on this subject, which describe his theory and the meaning of this computational model" (Barricelli, n.d.-a, p.23). The "more detailed papers" to which von Neumann refers presumably included Barricelli's 1947 theoretical paper on his gene-symbiosis hypothesis, mentioned earlier, and probably also what Barricelli elsewhere (Barricelli, 1953, pp.1, 12) referred to as a "preliminary communication" about his numerical models, entitled *Numerical models of evolutionary organisms*. We have been unable to trace a copy of this unpublished report,[5] but as far as we are aware it was the first paper he wrote about these models. We assume Barricelli wrote it in Oslo in 1951, and it is likely that the content was largely the same as the first half (sections 1–6) of the *Esempi Numerici* paper.

Over the next year various administrative difficulties delayed the progress of Barricelli's application, but von Neumann remained in correspondence with Frisch about the subject and assured him that "I [am] looking forward with great interest to Mr. Barricelli's visit, since I hold considerable expectations for the probable outcome of our cooperation" (Barricelli, n.d.-a, p.20). Von Neumann also wrote a letter of support of Barricelli's Fulbright grant application to the Fulbright office in Oslo, in which he stated "I have seen some of Mr. Barricelli's work on genetics, which struck me as highly original and interesting ... There are ... here several groups of researchers in this field who would be very interested in cooperating with Mr. Barricelli. This includes some of my associates and myself in Princeton. I have no doubt that Mr. Barricelli's visit would ... very probably be fruitful in relevant scientific results" (Barricelli, n.d.-a, p.19).

[5] During our search we enlisted the help of staff at the IAS Archives, the University of Oslo Archives, Barricelli's nephew Cato Brahde and half-nephew Ivar Aars, George Dyson, and Alexander Galloway, but without success.

2.4 Visit to IAS in the first half of 1953

Barricelli finally arrived in Princeton in January 1953 and worked at IAS for the first half of that year. The IAS Machine was generally employed in work relating to national defence during the days, so he usually worked the evening- or night-shifts allocated to users like himself.[6] Initial coding tasks included not only the programming of his numerical models but also the development of various "service" codes. For example, output routines needed to be written to calculate "the arrangement of decimal results on output cards so that these [could] be used directly on an IBM tabulator to give special arrangements of the data on the printed page" (The Staff, Electronic Computer Project, 1954, p.II-90); in this, as in his future work on the topic, Barricelli thought carefully about how best to visualise and present the results of his simulations (Galloway, 2012, pp.33–34). Furthermore, given the unreliability of the hardware, "[s]pecial attention was paid to ... the convenient re-use of output data as input after interrupted operation" (The Staff, Electronic Computer Project, 1954, p.II-83).

2.4.1 Production of the research report *Experiments in Bionumerical Evolution Executed by the Electronic Computer at Princeton, N.J.* (August 1953)

The accomplishments of his visit to IAS were summarised by Barricelli in a research report entitled *Experiments in Bionumerical Evolution Executed by the Electronic Computer at Princeton, N.J.*, dated August 1953 (Barricelli, 1953). This internal 26-page paper (together with an accompanying series of photographic plates showing output from some of the experiments) gave technical details of the design, execution and results of the 1953 runs—far more detail than appeared in the following year's *Esempi Numerici* publication.

Barricelli revealed in the *Experiments* report that he was using a universe size of 512 cells in his runs on the IAS Machine, in contrast to the maximum size of 83 cells he had used in his hand-calculated simulations. And he reported successful runs of up to 5400 generations in duration, compared to a maximum of 100 generations in the earlier hand-calculated runs. Other details in the report included specifics of nine different update rules ("norms") tested, and different ways of randomising the initial state using a pack of playing cards.[7] In order to avoid homogenization of the universe, several experiments were performed in which different norms were applied to different regions of the universe. Results from the runs were visualised in the form of photographic plates showing arrays of punched output cards; details of this visualisation technique were provided in an IAS project report produced the following year (The Staff, Electronic Computer Project, 1954) (see section 4.1).

Barricelli states that in his initial explorations with paper-and-pen simulations, no process of

[6] Details in these opening sentences were sourced from (Dyson, 2012, pp. 228, 230), (Barricelli, 1955, p.31) and (Gilchrist, 2006, p.6).

[7] Barricelli also states in the *Experiments* report that he used cyclic boundary conditions, so that the 512-cell universe was regarded as having a circular topology. This is a departure from his earlier hand-calculated experiments, which did not feature a circular topology (Barricelli, 1953, p.2).

evolution was observed. The larger simulations on the IAS Machine, however, had been more successful—the 1953 experiments provided the first (albeit modest) evidence that evolution was indeed possible in the numerical organisms. Barricelli reported that:

> "In most evolutionary processes observed only one or two hereditary changes have been able to expand; but in some cases even four or five changes have had the time to expand before the species was destroyed by concurrents or parasites or by some kind of disorganization process.
>
> "In no case has the evolution led to a degree of fitness which could make the species safe from complete destruction and insure an unlimited evolution process like that which has taken place in the earth and led to higher and higher organisms." (Barricelli, 1953, p.12)

Over half of the paper was devoted to describing specific instances of evolution in the organisms and investigating the sources of variation (mutations and crosses) that led to them.

Because the paper contains considerably more technical details than does the *Esempi Numerici* paper, we suggest that the *Experiments* report could justifiably be more widely cited as the earliest report of Barricelli's work. It was, however, an unpublished technical report, whereas *Esempi Numerici* remains the first journal-published account of his research on these topics.

Although it presented a great deal of technical detail and analysis, the *Experiments* report lacks several elements that were included in the *Esempi Numerici* paper (see section 3.2 for details): there is no discussion of the theoretical background on symbiogenesis or Darwinian evolutionary theory; there is no guided, illustrated run-through of Barricelli's initial hand-calculated experiments; and, there is no discussion of Barricelli's views on the ontological status of the numerical organisms in his artificial universe.

2.5 Conference attendances in the second half of 1953

Before writing up his work for journal publication, Barricelli presented it at a couple of conferences in Italy in the second half of 1953 after returning home from Princeton.

In late August he gave two presentations at the Ninth International Congress on Genetics, held in Bellagio on the shores of Lake Como. The English translations of the titles of his presentations are "*The use of self-reproducing numerical elements (numerical genes) to test the theoretical basis of the hypothesis of gene symbiosis*" and "*Numerical organisms and phenomena of a 'bionumeric' nature that appeared during experiments carried out using the electronic computer in Princeton, New Jersey, U.S.A.*".[8] We have not found any further details of these

[8]The titles in the proceedings are given in Italian:"L'impiego di elementi numerici autoriproduttivi (geni numerici) per verificare le basi teoriche dell'ipotesi della simbiosi dei geni", and "Organismi numerici e fenomeni di carattere «bionumerico» apparsi durante esperimenti eseguiti mediante il calcolatore elettronico di Princeton, New Jersey, U.S.A." (Montalenti & Chiarugi, 1953, p.81)

presentations, but the titles give a good idea of what was covered in them. The conference certainly gave Barricelli a good opportunity to disseminate his work to an illustrious audience; it was attended by close to 900 people, including J. B. S. Haldane, R. A. Fisher, L. S. Penrose, T. Dobzhansky, and C. H. Waddington (Montalenti & Chiarugi, 1953; Singleton, 1954).

In a letter to von Neumann dated 22 October 1953, Barricelli says that he also presented his work at the Institute for Telecommunications in Rome on the 10th of that month (Barricelli, n.d.-b, p.8). We have been unable to find any further details of that presentation.

2.6 Plans for a return visit to IAS in 1954

As soon as his first visit to Princeton was over in the summer of 1953, Barricelli applied to IAS on 30 July to return for a second visit in 1954. On 13 November 1953 official notice was received from Robert Oppenheimer, director of the institute, that his application had been successful. Barricelli therefore knew at the time that he was writing his *Esempi Numerici* paper that he would be returning to conduct further experiments on the IAS Machine.

3 Publication of *Esempi Numerici di Processi di Evoluzione*

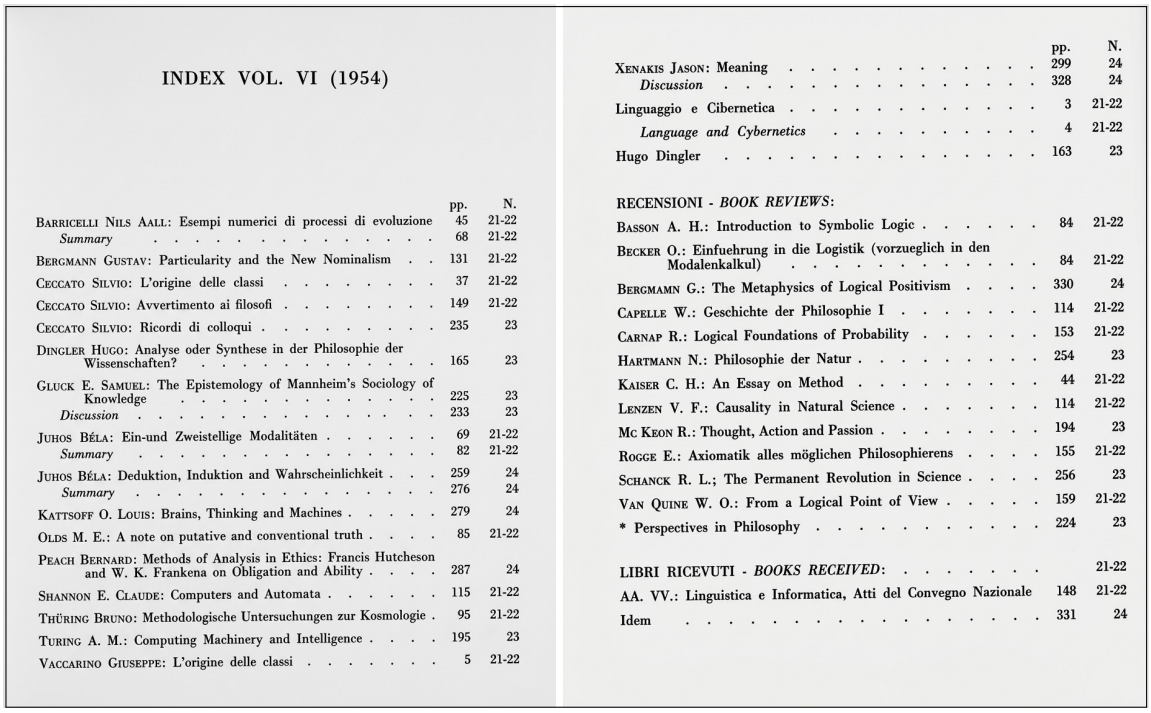
The 1953 *Experiments* paper was an internal report that had limited circulation at the time. The subsequent publication *Esempi Numerici di Processi di Evoluzione* was the first opportunity for the wider scientific community, beyond colleagues in Princeton and Oslo, to learn about Barricelli's experiments.

The paper was published in the Italian journal *Methodos*. The editors received Barricelli's submitted manuscript on 30 December 1953 and the final version appeared in a double issue of the journal (volume 6, nos. 21–22) in 1954.

3.1 The *Methodos* journal

Methodos was a publication of the *Centro Italiano di Methodologia e Analisi del Linguaggio (CIMA)* (the Italian Centre of Methodology and Analysis of Language) in Milan. The quarterly journal ran for sixteen volumes over the period 1949–1964, publishing articles written in English, Italian and German. Its initial focus had been on methodology and the analysis of thought and language, but by 1953 its scope had expanded to embrace new perspectives offered by recent developments in cybernetics and intelligent machines.[9] Other papers published in volume 6 included reprints of Claude Shannon's "Computers and Automata" and

[9]Historical details of CIMA are sourced from https://cency.info/italian-operational-school and https://matematica.unibocconi.eu/articoli/civiltà-delle-macchine-leonardo-sinisgalli-e-alan-turing. Note, by 1953 CIMA had been rebranded as the *Scuola Operativa Italiana* (the Italian Operational School).



INDEX VOL. VI (1954)

	pp.	N.
Barricelli Nils Aall: Esempi numerici di processi di evoluzione	45	21-22
Summary	68	21-22
Bergmann Gustav: Particularity and the New Nominalism	131	21-22
Ceccato Silvio: L'origine delle classi	37	21-22
Ceccato Silvio: Avvertimento ai filosofi	149	21-22
Ceccato Silvio: Ricordi di colloqui	235	23
Dingler Hugo: Analyse oder Synthese in der Philosophie der Wissenschaften?	165	23
Gluck E. Samuel: The Epistemology of Mannheim's Sociology of Knowledge	225	23
Discussion	233	23
Juhos Béla: Ein-und Zweistellige Modalitäten	69	21-22
Summary	82	21-22
Juhos Béla: Deduktion, Induktion und Wahrscheinlichkeit	259	24
Summary	276	24
Kattsoff O. Louis: Brains, Thinking and Machines	279	24
Olds M. E.: A note on putative and conventional truth	85	21-22
Peach Bernard: Methods of Analysis in Ethics: Francis Hutcheson and W. K. Frankena on Obligation and Ability	287	24
Shannon E. Claude: Computers and Automata	115	21-22
Thüring Bruno: Methodologische Untersuchungen zur Kosmologie	95	21-22
Turing A. M.: Computing Machinery and Intelligence	195	23
Vaccarino Giuseppe: L'origine delle classi	5	21-22
Xenakis Jason: Meaning	299	24
Discussion	328	24
Linguaggio e Cibernetica	3	21-22
Language and Cybernetics	4	21-22
Hugo Dingler	163	23
RECENSIONI - *BOOK REVIEWS*:		
Basson A. H.: Introduction to Symbolic Logic	84	21-22
Becker O.: Einfuehrung in die Logistik (vorzueglich in den Modalenkalkul)	84	21-22
Bergmann G.: The Metaphysics of Logical Positivism	330	24
Capelle W.: Geschichte der Philosophie I	114	21-22
Carnap R.: Logical Foundations of Probability	153	21-22
Hartmann N.: Philosophie der Natur	254	23
Kaiser C. H.: An Essay on Method	44	21-22
Lenzen V. F.: Causality in Natural Science	114	21-22
Mc Keon R.: Thought, Action and Passion	194	23
Rogge E.: Axiomatik alles möglichen Philosophierens	155	21-22
Schanck R. L.; The Permanent Revolution in Science	256	23
Van Quine W. O.: From a Logical Point of View	159	21-22
* Perspectives in Philosophy	224	23
LIBRI RICEVUTI - *BOOKS RECEIVED*:		21-22
AA. VV.: Linguistica e Informatica, Atti del Convegno Nazionale	148	21-22
Idem	331	24

Figure 3: Index of papers published in volume 6 of *Methodos* in 1954.

of Alan Turing's "Computing Machinery and Intelligence" (see Figure 3 for the full index of papers from this volume).

3.2 The *Esempi Numerici* paper

Although the *Esempi Numerici* paper was received at the *Methodos* editorial office in December 1953, four months after Barricelli wrote the *Experiments* report, it does not cover the technical details of the IAS experiments from 1953 that were presented in the earlier report. Instead, it sets out the scientific and theoretical motivation for the work in more detail than was given in the *Experiments* report, and guides the reader through the design of the numerical models, starting from the simplest kinds and progressively adding more complexity. Only towards the end of the paper does Barricelli briefly introduce his experiments performed on the IAS Machine in 1953, and outline his ideas for further experiments planned for a return trip to Princeton in the spring of 1954.

It is sometimes claimed in the literature that the *Esempi Numerici* paper was republished in 1957 in English, e.g., (D. B. Fogel, 2006). If this were true, it would render the current translation redundant. However, this is not the case. The 1957 paper, discussed further in section 4.4, was significantly different, presenting a much more comprehensive account of Barricelli's computational experiments at IAS in 1953 and during a return visit in 1954.

Looking at the contents of *Esempi Numerici* in a little more detail, Barricelli begins by arguing

that, while Darwin's theory of evolution by natural selection can explain the appearance of complex adaptations in biological organisms, it cannot answer the question of why organisms exist in the first place—it does not explain the origin of life. He then introduces simple versions of his numerical models, in which an array of numbers reside in a one-dimensional universe with discrete spatial locations and with update rules applied in discrete timesteps.

In the most basic model the update rules of the system are such that each existing number is copied to another location in the universe at the next time step, and in the case where two or more numbers land in the same location, a mutation rule is applied to place a new number in that location that might be different from any of those involved in the collision. Barricelli states that the system therefore implements the basic requirements for a Darwinian evolutionary process: the ability to reproduce, and the ability to undergo hereditary changes.[10] Discussing an example of this model in action, Barricelli notes that "[t]he numbers with the highest probability of survival in the environment created in Figure 1 by the rules we have chosen will live on. The rest will be gradually eliminated" (Barricelli, 1954, p.48) (English translation by authors). In other words, there will be a process of adaptation in which only numbers that co-exist with other numbers in the universe will survive (they can achieve this most reliably by not colliding with each other). But after describing the behaviour of this model, he concludes "something is still missing in order to explain the formation of organs and faculties as complex as those of living organisms. No matter how many mutations occur, the numbers [in this model] will remain numbers forever. They will never become living organisms!" (Barricelli, 1954, p.48) (English translation by authors).

Barricelli then introduces Kozo-Polyansky's symbiogenesis theory as a possible answer to the "something" that was missing from his model. He shows how this might be incorporated into his numerical models using rules to implement what he calls the "utilitarian association" of numbers in the universe. Barricelli goes on to discuss example models that incorporate this feature, first without mutations and then with mutations included. These models show some promising properties, such as the ability to cross two different "numerical organisms" to produce a new type that contains elements of both parents.

With the addition of these rules for utilitarian association, single numerical elements can no longer reproduce by themselves but only with the help of other elements. In this context, a "numerical organism" is a continuous sequence of numerical elements (and possibly empty spaces) that can make additional copies of itself by means of the collective, reciprocal (symbiotic) actions of its constituent elements. Likewise, a "species" is a class of numerical organisms with a particular arrangement of constituent elements.[11] The crossing experiments demon-

[10] We note that Barricelli's list is missing any explicit mention of the idea of selection (differential reproduction), which is widely accepted as a requirement for Darwinian evolution, e.g. (Lewontin, 1970). But the discussion of adaptation that follows demonstrates an implicit selection pressure even in his simplest models for stable configurations of numbers that can co-exist with each other. And in the crossing experiments with more complex models, described later in the paper, there is clear evidence of differential reproductive success between different numerical organisms in a given environment in cases where one parent survives a cross whereas the other parent does not.

[11] Note that the numerical organisms of a species generally reproduce asexually, although they can sometimes

strate that numerical organisms can undergo hereditary changes, and that they therefore fulfil the requirements for a Darwinian evolutionary process.

The most complex result described in the paper involves a universe of size 83 locations, where the initial state of each location was set at random to either a +1 or -1 (with 25% chance for each of these) or left empty (with 50% chance). Barricelli calculated the evolution of this universe over 100 generations. The results are shown in Figure 15 in the paper, which fills two whole pages in the *Methodos* version. Barricelli described some of the most interesting results observed in this figure, including the appearance of new species of numerical organisms on various occasions during the experiment, even though the universe had started in a random state. Furthermore, organisms of some of these species were unable to reproduce by themselves but lived as parasites on other species. Although new species like these sometimes appeared, either through the application of mutation rules, or by the crossing of two parent organisms, Barricelli did not observe any examples of the gradual Darwinian evolution of a species after it had emerged. He remarks "All the species in Figure 15 are very primitive and have not exhibited any instance of evolution."

At this stage, Barricelli had clearly got as far as it was practically possible to go in exploring these models using paper and pen. Indeed, as we have discovered, he made several errors in his calculations of Figure 15 (see section 5.3 of this commentary). He says "[t]o develop more complex organisms, the experiment conducted in Figure 15 must be repeated on a much larger scale. This is possible, in practice, only by using large computing machines." So finally, in section 7 of the paper, we get to a discussion of the experiments conducted on the IAS Machine in Princeton.

As we stated previously, Barricelli does not provide much detail about the Princeton experiments. He does say that he had been able to run experiments in a universe of size 512 locations for 5400 generations—a significant improvement over his largest hand-calculated experiments featuring 83 locations for 100 generations.

The most interesting fact that we learn about the experiments is that "[i]t quickly became apparent that, by employing the same reproduction and mutation rules throughout the entire 'Universe,' evolution led to homogeneity within a few hundred generations. ... In order to prevent [this], it was necessary to divide the 'Universe' into different regions, each with its own set of rules. ... Several experiments were performed by modifying the rules used and the number and dimensions of the regions."

Present-day researchers in artificial life and open-ended evolution will be all too familiar with this problem of evolution in this kind of system grinding to a halt after a while. We see here that this is by no means a new problem, and that Barricelli recognised it in the very first experiments with computational evolution.

be crossed with organisms of other species to create offspring of a new species. Barricelli's concept of a species in this work is therefore more akin to some definitions of bacterial species in the biological sense than it is to sexually-reproducing species.

Barricelli reports that he did observe "[v]arious evolutionary processes lasting several hundred generations"—although these were still relatively short-lived in the context of a 5400-generation experiment. He adds that, "[m]ore often than not, the process halts when the species reaches a so-called 'relative maximum of fitness'" (i.e. a local optimum in the fitness landscape, to use today's terminology), although he notes that sometimes a species can escape this if a change in a neighbouring species results in a change in the fitness landscape.

Despite these evolutionary processes being relatively short-lived, the experiments run on the IAS Machine in 1953 and first openly published in this paper were the earliest documented examples of evolution occurring in a computational universe.

Discussing the further experiments he intended to conduct during his planned return trip to IAS in 1954 (section 8), Barricelli makes it clear that his goal would be to achieve the open-ended evolution of numerical organisms: "The initiation of an unlimited evolutionary process will by the main aim of the research". In order to achieve this, in addition to experimenting with different rules, he also mentions plans to investigate a two-dimensional universe which would allow for a wider variety of interactions between organisms.

Finally, in the brief concluding section of the paper (section 9), Barricelli raises the question of whether his numerical organisms should be considered as living organisms (rather than just simulations of living organisms). Declining to take a strong view in either direction, he says "Whether or not we want to acknowledge them as living organisms may ultimately be a matter of definition."

4 Relation to Barricelli's later works

Over the next 20 years Barricelli experimented with extended versions of his numerical organisms and related models. These studies were conducted during return trips to Princeton in 1954 and 1956, and also during employment at several other U.S. universities as advanced computing facilities became more widespread. The results were published in various journals, mostly in English. In this section we give a brief description of these later publications and of how they related to the *Esempi Numerici* paper.

4.1 *Final report on contract no. DA-36-034-ORD-1023* (IAS report, April 1954)

In April 1954, the staff of the Electronic Computer Project produced a report entitled *Final report on contract no. DA-36-034-ORD-1023* (The Staff, Electronic Computer Project, 1954). This was an end-of-contract summary of research that included a description of Barricelli's 1953 experiments along with a great deal of other work conducted by staff of the Electronic Computer Project and funded by several research contracts (the full report is over 400 pages long).

A description of Barricelli's experiments appears on pages II-77 to II-93. This comprises a summary of the material already presented in the *Experiments* paper (most of which is directly quoted from the earlier paper), together with some brief comments at the end about service code developed to help with outputting data in graphical form onto punched cards. The paper includes a single figure of a photographic plate showing the output of a run from the IAS Machine; this is actually a section of Figure 1D from the 1953 report. It also gives some technical details of how the punched cards were arranged, photographed and further assembled into the large plates shown in the figures of the *Experiments* paper.

4.2 *5400 Generazioni* (Civiltà Delle Macchine, 1955)

While researching this commentary we came across a 1955 publication by Barricelli that we had previously been unaware of, in the Italian journal *Civiltà Delle Macchine* (Machine Civilisation). The journal had been founded two years previously, with a focus on the intersection of science, technology, culture and art (Fondazione Ansaldo, n.d.).

Barricelli's paper, written in Italian and entitled *5400 Generazioni*, appeared in the May–June 1955 issue of the journal. He clarifies for the reader that he is not trying to model the early stages of biological evolution specifically. Rather, his aim is:

> "to investigate whether evolutionary processes based on the same principles that supposedly govern biological evolution are possible, and how they would initially unfold, starting from numerical elements or any other kind, even if completely different from viruses and genes, provided they are capable of reproducing, undergoing heritable mutations, and associating in organisations (symbioorganisms) that offer a selective advantage." (Barricelli, 1955, p.30) (English translation by authors)

This is the first time Barricelli introduces the term "symbioorganism", which he coins as an umbrella term to describe both biological and artificial organisms that possess the properties stated in the quote. In so doing, he is able to some extent to bypass questions about whether his numerical organisms are "alive" — instead, they are examples of the higher category of symbioorganisms, as are biological organisms.

5400 Generazioni includes a more-or-less verbatim reproduction of the *Esempi Numerici* paper, along with a considerable amount of extra detail and analysis of the experiments on the IAS Machine, plus some well-designed images of the outputs featuring added colour annotations to clearly demarcate different species of symbioorganisms.

The paper also includes some brief preliminary discussion of experiments conducted by Barricelli at IAS during his second visit in 1954. Barricelli says that in these later investigations he was able to observe evolutionary processes that continued "until the end of the experiment,

that is, for several thousand generations" (Barricelli, 1955, p.31). He also reports that, as promised in the *Esempi Numerici* paper, he tried some experiments where numerical elements were placed in a two-dimensional universe. The results were apparently successful, although no details are given in this paper. They were convincing enough to lead Barricelli to the following conclusion:

> "Evolutionary processes according to the principles of biological evolution, in which interbreeding (or sexual reproduction) plays a predominant role, can be achieved with many types of elements capable of reproducing, mutating, and associating in symbioorganisms. Therefore, this is not a phenomenon specific to a particular type of element, such as deoxyribonucleic acid molecules (viruses and genes), but a general statistical phenomenon affecting many types of elements with the aforementioned properties." (Barricelli, 1955, p.31) (English translation by authors)

This passage clearly demonstrates Barricelli's functionalist position on the ontological status of his numerical organisms as symbioorganisms.

4.3 *Symbiogenetic Evolution Processes Realized by Artificial Methods [part 1]* (Methodos, 1956)

Barricelli published a short (9-page) paper, in English, in a 1956 issue of the *Methodos* journal (Barricelli, 1956). In it he mostly discusses the scientific motivation for his work. He talks briefly about symbiogenesis theory, but also adds a discussion of the discovery of the structure of DNA by Watson and Crick, and suggests that experiments with his numerical models might inform the design of evolutionary experiments using real DNA molecules.[12]

Interestingly, having usefully introduced the term symbioorganism the previous year (Barricelli, 1955) to allow him to bypass the question of whether his numerical symbioorganisms are living beings, Barricelli suggests more strongly than ever in this paper that they could indeed be considered alive:

> "None of the properties required of a gene by the symbiogenesis theory seems to be of a definitely chemical nature; nor are the properties those which one would expect to find only in certain albumen [*sic*] molecules. Just because the special conditions prevailing on this earth seem to favor the forms of life which are based on organo-chemical compounds, this is no proof that it is not possible to build up

[12]The *5400 Generazioni* paper from 1955 also included a brief discussion of the discovery of DNA in an endnote in italic font (DNA is also referred to one other time in the paper, but without further elaboration, in the text quoted at the end of section 4.2). It is unclear whether the endnote was authored by Barricelli or by the editors of the journal, but the discussion makes no attempt to directly relate this discovery to Barricelli's models.

> *other forms of life* on an entirely different basis." (Barricelli, 1956, pp.307–308) (emphasis added)

The paper is riddled with typographical errors and appears to have been published with little editorial oversight. It shows some figures of Barricelli's early paper-and-pen experiments (which appeared as Figures 1–6 in the *Esempi Numerici* paper), but these figures are out of context and are not referred to in the text. The paper ends quite abruptly, with a note to say it will be continued in the next issue of the journal.

The paper was intended to be the first half of a two-part article. However, in light of the various errors and problems with the paper, the editors decided that the next publication, which appeared in 1957 (described in the following section) should be a stand-alone publication covering all of the material originally planned for parts 1 and 2, with the various problems of the 1956 paper corrected and with a substantial amount of new material added.

4.4 *Symbiogenetic Evolution Processes Realized by Artificial Methods* (Methodos, 1957)

Whereas the 1955 paper *5400 Generazioni* had presented some brief initial remarks about the experiments conducted during his second visit to IAS in 1954, Barricelli's 39-page paper *Symbiogenetic Evolution Processes*, published in *Methodos* in 1957 (Barricelli, 1957), presents a full analysis of those experiments, as well as of those conducted on his first visit in 1953. The 1957 paper also includes some introductory discussion of symbiogenesis theory and of Barricelli's original paper-and-pen experiments. It is therefore the first journal publication that gives a comprehensive introduction, description and analysis of Barricelli's experiments at IAS during his first two visits in 1953 and 1954.

Barricelli reports how a small but significant change in the system's norms in the 1954 experiments—which prevented small parasites from reproducing at a much faster rate than larger symbioorganisms—led to much longer periods of evolution in the system. In addition, long-lasting evolution was aided by having multiple universes running in parallel (he used three in the experiments reported here), with occasional interchanging of elements between them, and also by employing the technique first discussed in *Esempi Numerici* of using different norms in different regions of each universe. Indeed, Barricelli says that, with these changes, he has "every reason to believe that an unlimited evolution process can be realized by the [symbioorganisms]" (Barricelli, 1957, p.174)

Regarding the status of the symbioorganisms as living beings, the quote given above from the previous paper about the possibility of creating "other forms of life" appears in this paper too (Barricelli, 1957, p.146).

The paper concludes with some general lessons that Barricelli believes would apply to any attempt to design an open-ended evolutionary process:

> "Make life difficult but not impossible for the simbioorganisms [*sic*], let the difficulties be various and serious but not too serious; let the conditions be changing frequently but not too radically and not in the whole universe at the same time; then you may see an evolution transforming the symbioorganism with a surprising rapidity and creating properties and organs which will make the symbioorganism able to face all the difficulties and all the new situations it meets. But do not expect to observe an evolution process if you let the symbioorganism vegetate in peace and safety in a perfectly homogenious [*sic*] universe. In that case you will probably observe nothing essentially more complicated than the simplest molecule." (Barricelli, 1957, p.175)

4.5 Later publications (1962–1991)

After his second visit to IAS in 1954, Barricelli worked in biology and genetics departments at various American universities until returning to the Institute of Mathematics at the University of Oslo in the late 1960s. He spent significant time at the University of Rochester, NY (1956–1958),[13] at Vanderbilt University in Nashville, TN (1959–circa 1963),[14] and at the University of Washington in Seattle, WA (1964–1968).[15] In this period he also had shorter visits to various other institutions to use their computing facilities, including the IBM 704 at the AEC Computing Center at New York University in 1959, the IBM 704 at Brookhaven National Laboratory (Long Island, NY) in 1960,[16] the Atlas machine at Manchester University (UK) in 1962-63,[17] and the IBM 7094s of the Western Data Processing Center and the Health Science Computing Facility, both at UCLA, in 1963-64.[18,19]

[13]Barricelli's arrival and departure dates at the University of Rochester are confirmed in (University of Rochester, n.d.). He worked there as a Research Associate in A. H. (Gus) Doermann's virus genetics group in the Department of Biology. It appears that Doermann became something of a mentor, and Barricelli followed him when Doermann moved from Rochester to Vanderbilt and then from Vanderbilt to Washington. Indeed, of the last move from Vanderbilt to Washington, Frank Stahl says that "Doermann had taken a job in Seattle and brought Nils with him" (Stahl, 2007).

[14]Barricelli's start date at Vanderbilt is confirmed in (Beach, 1958). His exact date of departure is not clear, but a notice for the talk he gave at the University of Manchester in February 1963 still lists Vanderbilt as his institution (Rutherford Laboratory Bulletin, 1963).

[15]These dates were verified by Massimo Passamonti by studying grant proposals that mention Barricelli in Doermann's archived files at the University of Washington (Passamonti, 2026). The start date ties in with Doermann's arrival in Seattle in 1964 (Stadler, 1992). In addition, Tor Gulliksen's obituary for Barricelli states that his time working at American universities ended in 1968 (Gulliksen, 1993).

[16]Barricelli gives brief details of his visits to the AEC Computing Center and Brookhaven National Laboratory in (Barricelli, 1963).

[17]Barricelli arrived in Manchester in 1962 (Bell, 1978, p.49). He gave a talk in Manchester on 25 Feb 1963 about the results of the experiments he had run on the Atlas (Rutherford Laboratory Bulletin, 1963).

[18]Biologist Richard E. Goodman recalls Barricelli arriving at UCLA as a visiting scientist in 1963 and having access to the facilities of the university's Western Data Processing Center (Goodman, 2012). Elsewhere, Barricelli states that some of the reported experiments in the paper were run on the facilities of the UCLA Health Science Computing Facility "in the period 1963 to 1964" (Barricelli & Toombs, 1971b, p.623).

[19]Barricelli not only used these various computing facilities to run his numerical symbioorganism experiments, but also for other work, such as simulating the evolution of virus genetics (Barricelli & Toombs, 1971a, 1971b;

Over this period, Barricelli expanded the breadth and depth of his computational studies into the evolution of symbioorganisms. He published a definitive English-language account of his work up to the early 1960s as a two-part paper in consecutive issues of the Dutch journal *Acta Biotheoretica* (Barricelli, 1962, 1963).

Part One of the paper presents a comprehensive account of the theory behind the work and of experimental results reported in earlier publications,[20] before discussing previously-unreported experiments performed during Barricelli's third and final visit to IAS in 1956. In this work he ran a somewhat larger-scale evolutionary experiment than the one he ran two years earlier (using five parallel universes instead of three, and running for 5000 generations instead of 3000). The most notable new contribution in the paper is an analysis of a series of competition tests in which Barricelli pits symbioorganisms present at various different stages of the evolutionary run against each other. He demonstrates that those that appeared later in the run were able to displace those from earlier periods, concluding that "it is clear that the ability to survive is improved by evolution" (Barricelli, 1962, p.92).

Interestingly, the paper starts with a "*Note by the author*" in which Barricelli assures readers that his numerical organisms do not represent a "new type of life", but rather that they, and biological organisms, both represent instances of "a larger class of symbioorganisms" (Barricelli, 1962, p.69). He goes on to explain that any biological terminology he uses to describe his organisms is used because it is "easy to remember" and makes "the analogies with biological concepts immediately clear", but warns the reader "not to confuse a term used in connection with symbioorganisms with the same . . . term used in biology" (Barricelli, 1962, p.70). These statements are something of a reigning in—or certainly a clarification—of the more forthright comments made in the *Symbiogenetic Evolution Processes* paper (Barricelli, 1956).[21]

Building upon the competition tests reported in Part One, the first section of Part Two of the paper addresses the question of "whether it would be possible to select symbioorganisms able to perform a specific task assigned to them" (Barricelli, 1963, p.100). Barricelli viewed this as an attempt to add "bodies" or "somatic structures" to his symbioorganisms, allowing them to do other things beyond simply reproducing. He describes experiments in which specific regions of a symbioorganism were interpreted as an encoded strategy for playing a simple board game.[22] This mechanism was used to resolve collisions—when two symbioorganisms tried to move into the same location, they competed in a game using their respective strategies, and the victor won the right to the contested location. The experiments provided some limited

Barricelli et al., 1971).

[20]This section of the paper was based upon a departmental report Barricelli had written at Vanderbilt University three years earlier (Barricelli, 1959).

[21]We note that all of Barricelli's more forthright comments on the status of his numerical symbioorganisms as living beings were made in papers published in the *Methodos* journal. It is possible that his changing statements on the matter were influenced more by the editors of the journals in which they were published than by Barricelli's own thoughts on the matter.

[22]The board game was a variant of the classic game *Nim*, called *Tac Tix*, which had recently been described by Martin Gardner in his *Mathematical Games* column in the journal *Scientific American* (Gardner, 1958, pp.104–111).

hints that evolution could improve the organisms' strategies over time, but the results are not really convincing and would need more experimentation to produce statistically sound conclusions. Barricelli's general conclusion from these experiments nevertheless demonstrates the motivation behind these experiments:

> "It has been shown that given a chance to act on a set of pawns or toy bricks of some sort the symbioorganisms will 'learn' how to operate them in a way which increases their chance for survival. This tendency to act on any thing which can have importance for survival is the key to the understanding of the formation of complex instruments and organs and the ultimate development of a whole body of somatic or non-genetic structures." (Barricelli, 1963, p.117)

In the final section of Part Two of the paper, Barricelli discusses whether symbioorganisms could be instantiated in other media, and in particular in DNA molecules (an idea that he had briefly mentioned previously in (Barricelli, 1956)). He considers numerical experiments based upon rules specifically modelled on the properties of DNA, and also discusses using DNA molecules themselves to create "chemo-analogical computers" (pp.121–122). The latter idea pre-dated by 30 years the growth of the field of DNA computing after Barricelli's death, from the 1990s onwards (Xu et al., 2025).

A decade later, Barricelli's final substantial journal paper on numerical symbioorganisms was published in the *Journal of Statistical Computation and Simulation* (Barricelli, 1972). This largely recapped earlier work, most of which had already been covered in the *Acta Biotheoretica* papers. It also referenced work with a different evolutionary system developed by Jon Reed (a young mathematician at the University of Oslo) and Robert Toombs (a student at the University of Washington) in collaboration with Barricelli (Reed et al., 1967).[23,24] In addition, Barricelli briefly discussed work done during his visit to Manchester University in 1962–63, where he pursued further experiments with encoding strategies for games including chess (Barricelli, 1972, p.121).[25] However, none of these attempts was very fruitful—Barricelli admits that "[r]esults more encouraging, with respect to the possibility of practical applications, have been obtained in cases in which a different approach to the determination of a game strategy was possible," such as in the work with Reed and Toombs which was not based upon

[23]Biographical details in this paragraph are sourced from (D. B. Fogel, 2006) and (University of Oslo, 2024).

[24]This work was inspired by Barricelli's earlier publications, and has been described by David B. Fogel as "a truly remarkable contribution to the history of evolutionary computation" (D. B. Fogel, 2006, p.42). It is unclear how actively Barricelli was involved in the design of this alternative system, and a planned follow-up paper was never published (D. B. Fogel, 2006, p.45).

[25]Alex Bell, a young computer scientist in Manchester at the time, was hired to help develop Barricelli's chess program for the Atlas. He provides a brief account of this time in (Bell, 1978, pp.49–50). Bell states that "this was probably the first fully legal chess program to run in England (possibly the world)" (Bell, 1978, p.50). Barricelli maintained an active interest in computer chess programs in later years. In 1974 he entered the First World Computer Chess Championship in Stockholm with his own chess program *Freedom*, which finished tenth out of thirteen entries (Hayes & Levy, 1976, p.50). *Freedom* does not appear to have been based upon Barricelli's numerical evolution work (Hayes & Levy, 1976, pp.76-77).

symbioorganisms. Nevertheless, he still emphasized the importance of crossover mechanisms for maximising the speed of evolution, and suggested that biological evolution (unlike his numerical system) is particularly powerful because the building blocks that it uses—nucleic acids and proteins—together with the mapping between them, have themselves "always been built exclusively by Darwinian trial and debugging processes" and are therefore "specifically adapted" for evolvability (Barricelli, 1972, p.126).

Barricelli published no further journal papers on his numerical organisms after 1972. In correspondence with the Nobel Prize-winning biologist Sydney Brenner in August 1985, Barricelli states that his "work with numeric evolution by computer has been interrupted more than 15 years" (Barricelli, 1985). He did publish an article in a 1987 issue of *Theoretic Papers*, a preprint journal produced by Barricelli's research group (the *Blindern Theoretic Research Team*) at the University of Oslo (Barricelli, 1987).[26] In this he proposes extensions to his early models that would allow symbioorganisms to evolve operational structures—such as membranes—through which they could regulate their environment. Evolution would then proceed via the world's general laws rather than a predefined game, with a clearer genotype–phenotype distinction and an emergent "genetic language" for specifying structure and organisation. By this point in his career, Barricelli was not proposing to undertake new experiments himself; instead, the paper is framed as guidance for a future implementer. A 1991 issue of *Theoretic Papers* contained a couple of reprints of earlier papers, each preceded by a short introduction, but with no substantial new content (Barricelli, 1991).[27] Barricelli became ill that year and died two years later at the age of 81.

4.6 Summary of content of Barricelli's main publications

Table 1 presents a concise summary of the main features of Barricelli's publications on numerical models of symbioorganisms. The table gives a clear picture of how his work and thinking developed over the twenty-year period from 1953 to 1972. It provides an at-a-glance summary of the contributions of the 1954 *Esempi Numerici* paper—Barricelli's first journal publication on this line of work—and how they relate to his earlier and later papers. The table concentrates on Barricelli's full publications in journals; with the exception of the first IAS technical report (Barricelli, 1953) it does not include unpublished reports or articles in the *Theoretic Papers* series.

[26] Barricelli secured funding for the journal (Ø. Aars, 1993), and it appears to have functioned largely as a publication vehicle for his own papers.

[27] The inaugural *European Conference on Artificial Life* took place in December of the same year in Paris—a short flight away from Oslo. Sadly, Barricelli did not attend the conference. Whether this was because of his illness, or he did not know about the conference, or was not interested in attending, we do not know.

Table 1: Feature matrix summarising Nils Aall Barricelli's computational evolution papers (1953–1972). + = explicit/central/yes; (+) = mentioned/implied/partial; — = absent/no. Light grey cells indicate the first implied/brief coverage/presence of a feature; darker grey cells indicate the first explicit/extensive coverage/presence.

Feature	1953 IAS	1954 Met	1955 CdM	1956 Met	1957 Met	1962 AB	1963 AB	1972 JSCS
Language: (E)nglish, (I)talian	E	I	I	E	E	E	E	E
Journal publication	—	+	+	+	+	+	+	+
Theoretical background on symbiogenesis	—	+	+	(+)	(+)	+	—	(+)
Hand-worked numerical examples	—	+	+	(+)	+	+	—	+
Detailed technical discussion of system	+	—	+	—	+	+	+	+
Analysis of 1953 IAS experiments	(+)	+	+	—	+	+	—	+
Analysis of 1954 IAS experiments	—	—	(+)	—	+	(+)	—	(+)
Analysis of 1956 IAS experiments	—	—	—	—	—	+	—	+
Analysis of post-1956 experiments	—	—	—	—	—	—	+	+
Mentions collaboration with Reed & Toombs	—	—	—	—	—	—	—	+
Heterogeneous norms / regions	(+)	+	+	—	+	+	+	+
Multiple universes & exchange	—	—	—	—	+	+	+	+
Aim of unlimited / open-ended evolution	(+)	+	+	(+)	+	+	(+)	+
Uses term "symbioorganism"	—	—	+	+	+	+	+	+
Strong "other forms of life" stance	—	(+)	—	+	+	retreat	—	—
Competition tests (later beats earlier)	—	—	—	—	—	+	(+)	+
Task / game-based selection (Tac Tix, Chess)	—	—	—	—	—	—	+	(+)
DNA / chemo-analogical computing link	—	—	—	(+)	(+)	(+)	+	(+)
2D spatial experiments	—	(+)	(+)	—	+	—	(+)	—

Column key: **1953 IAS** = IAS internal report (Barricelli, 1953); **1954 Met** = *Methodos* (Barricelli, 1954); **1955 CdM** = *Civiltà delle Macchine* (Barricelli, 1955); **1956 Met** = *Methodos* Part 1 (Barricelli, 1956); **1957 Met** = *Methodos* (full paper) (Barricelli, 1957); **1962 AB** = *Acta Biotheoretica* Part 1 (Barricelli, 1962); **1963 AB** = *Acta Biotheoretica* Part 2 (Barricelli, 1963); **1972 JSCS** = *Journal of Statistical Computation and Simulation* (Barricelli, 1972).

5 Translating the paper

In this section we provide some comments on the process of translating the *Esempi Numerici* paper, and describe some issues that arose while doing so.

5.1 Writing style and approach to the translation

A modern reader encountering the original Italian text of *Esempi Numerici* may be struck by the contrast between the highly technical subject matter and the rhetorical style in which it is presented. Although the paper reports numerical and computational experiments, parts of the text—particularly the introductory and final sections—are written in a reflective and philosophical tone. This is evident from the opening question, "Come mai esistono gli esseri viventi?" ("Why do living organisms exist?"), which establishes the broader motivation for the work.

This style reflects the intellectual and educational context in which the paper was written. During the interwar period, many Italian scientists received a strongly humanistic education (Agazzi, 1972). Barricelli himself states that he completed the classical branch of the Italian *Artium* examination in 1932 (Barricelli, n.d.-a, p.14), indicating that he had followed the *liceo classico* curriculum, with its emphasis on Latin, Ancient Greek, philosophy, and the history of ideas.

It is also worth noting that Barricelli later translated and reworked parts of this material in several English-language publications, particularly in his Vanderbilt departmental report (Barricelli, 1959) and in the comprehensive account in *Acta Biotheoretica* (Barricelli, 1962). As discussed in section 4, Barricelli repeatedly revisited and revised the same core material throughout his career, expanding and refining both the theoretical discussion and the presentation of the experiments.

Rather than adopting Barricelli's later English translations directly, we chose to work primarily from the original Italian text of *Esempi Numerici*, while aiming to produce a version that remains readable for a contemporary English-speaking audience. The Vanderbilt report was particularly useful during the preparatory stages of the translation. We first compiled a glossary of recurring technical terms through a corpus-based analysis of the Italian text, and then compared these with the terminology used in Barricelli's later English-language publications in order to identify historically appropriate equivalents. Much of the subsequent revision involved adjusting syntax and vocabulary to balance fidelity to the original text with readability in contemporary English.

An interesting aspect of the paper is the way in which a style shaped by Italian humanistic traditions is combined with an attempt to formulate biological and evolutionary processes in explicitly formal and computational terms. In preparing the translation, we have tried to preserve something of this distinctive combination of styles while still producing a clear and

accessible English text.

5.2 Reproduction of the figures

The legibility of some of the figures in the original paper was poor, so we decided to create new versions of all of them for use in the translated paper. The easiest way to do this, especially for the larger ones, was to recreate Barricelli's simulations ourselves by writing a new simulator following the descriptions in the paper and using it to regenerate each of the figures. The additional advantage of this approach is that it forced us to clarify and understand all of the details of the simulations.

Our new simulator is written in C++ and is freely available on GitHub (Taylor, 2025). The repository also contains versions of each of the figures from the paper in CSV and PNG formats. The update methods of the main source file of the simulator are heavily commented to describe each step of the simulation.

Using this approach, we were able to recreate all but one of the figures in the paper with little trouble. However, we encountered problems when trying to recreate Figure 15, the largest figure. The output we created matched Barricelli's for the first eight generations, but diverged thereafter (compare Figures 4 and 5 of this commentary).

5.3 Errors in Figure 15

Inspection of the Figure 15 output produced by our simulator compared to the figure in the original paper revealed that the content of three cells in the universe differed in generation 9.

We consulted with Barry McMullin of Dublin City University, whose student Lalaina Rahobisoa had recreated Barricelli's simulator in Java during an internship project in 2011 (Rahobisoa, 2011). Prof. McMullin kindly supplied us with Rahobisoa's original code and internship report. It turned out that in order to reproduce Figure 15 as it appeared in Barricelli's papers, Rahobisoa had to make changes to "around 80" cells in the 100 generations of the 83 cell universe, so around 1% of the cells.

Furthermore, we have discussed the discrepancy in Figure 15 with Massimo Passamonti at the University of Cambridge, who has also recently written a simulator and tried to reproduce these figures. His output for Figure 15 matches ours, which gives us additional confidence that the errors lie in the version published in the *Esempi Numerici* paper rather than in ours.

Accepting that the original Figure 15 was erroneous, and considering that Barricelli included it not only in the 1954 paper but also in many of his later publications right up to his final substantive writing on the subject (Barricelli, 1987), one might ask whether this has a significant bearing on his analysis and discussion. In the *Esempi Numerici* paper Barricelli explains

Figure 4: Reproduction of the original version of Barricelli's Figure 15 from the *Esempi Numerici* paper, using data generated by Lalaina Rahobisoa (2011).

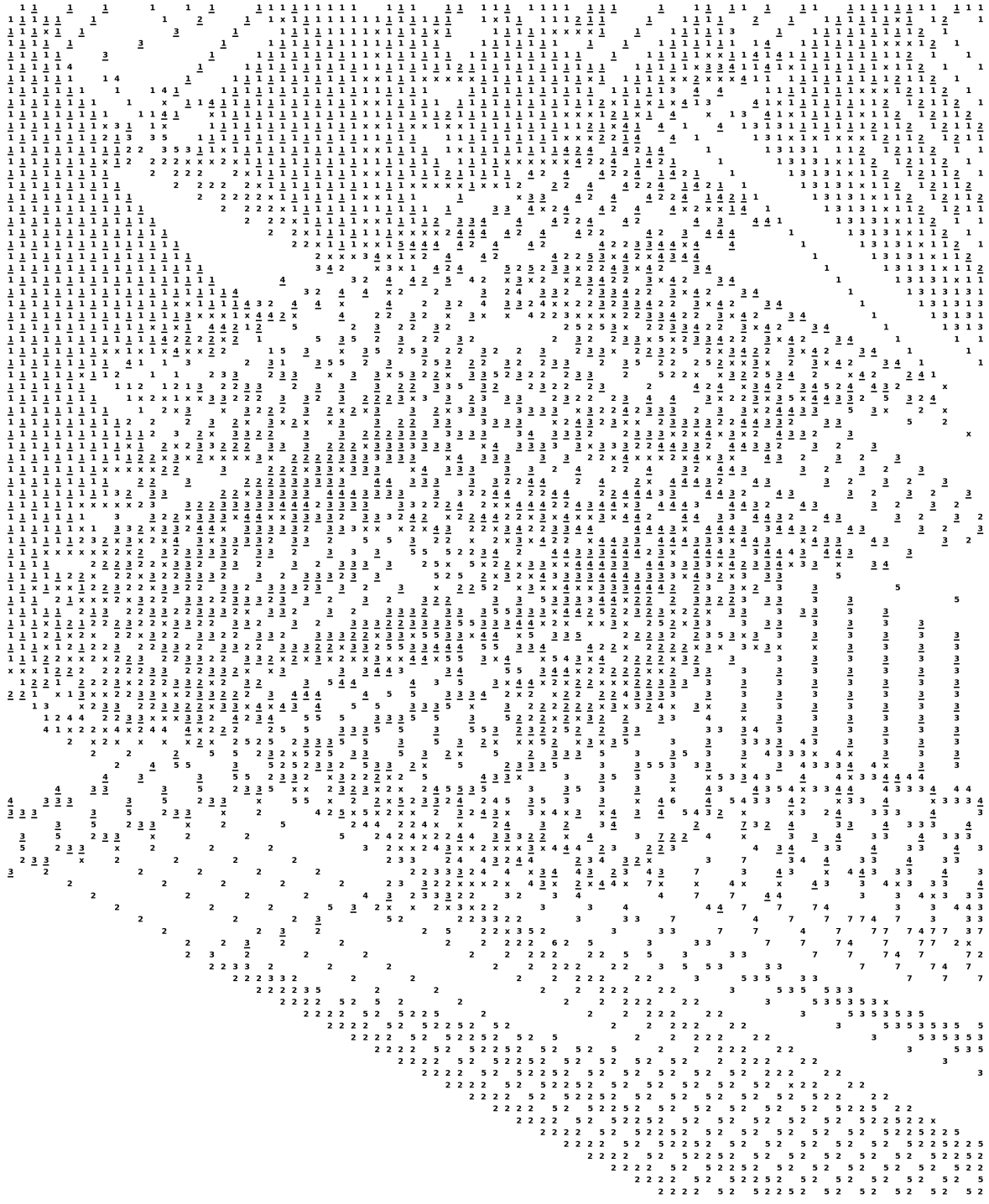


Figure 5: The output of our simulator when re-running the initial conditions described by Barricelli for his Figure 15.

that he populated the initial generation of the universe with the numbers 1, 0 and -1 drawn at random with probabilities 25%, 50% and 25% respectively (see section 3.2 of this commentary). In order to get a better feeling for the general behaviour of this configuration of the system, we generated 100 different starting states for the universe using the same probability distribution employed by Barricelli and visually inspected the results. The output of a randomly selected sample of nine of these runs is shown in Figure 6.[28]

A visual inspection of the results showed that some of the runs produced outputs with dynamics that looked similar to those shown in Barricelli's original figure, while others did not.

We can perform a coarse-level analysis of these runs by categorising the activity in the final 10 (say) generations as either *static*, *cyclic*, *glider* or *complex*. In static universes there is no change in the state of the cells from one generation to the next next. In cyclic universes we see a short cycle of states repeating across the generations (in these 100 runs, we only saw cycles of length 2 or 3 generations). In glider universes, we see one or more short patterns that move diagonally across a static or cyclic background as the generations progress. Finally, in complex universes we see dynamics that do not fall under the previous three categorisations. Each of the subplots in Figure 6 has been labelled with the resulting classification for that run.

We wrote a script to automatically categorise a run's output in this way, and verified that its classifications agreed with a visual inspection of the output of each of the 100 runs.[29] Having done this, we then performed a larger series of 10,000 runs of the Figure 15 configuration with random starting positions, and used the script to automatically classify their dynamics. The results showed that 1.18% of the runs ended with static dynamics, 23.44% were cyclic, 54.64% were gliders, and 20.74% were complex. Running the script on Barricelli's original (erroneous) version of Figure 15 produces a classification of *complex*. We can therefore conclude that the original version of Figure 15 that appeared in the *Esempi Numerici* paper, while containing some errors, was nevertheless illustrative of the dynamics observed in over 20% of runs of this configuration starting with randomly generated initial conditions. These complex dynamics are the most interesting category, so it appears that Barricelli was reasonably lucky to have generated an output that displayed this category of dynamics[30] but that his subsequent analysis was still applicable to one in five of all runs of the system.

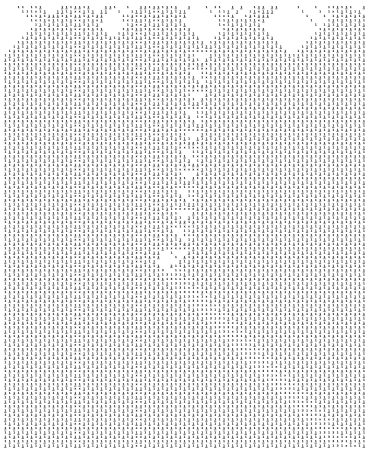
5.4 Dual use of the "x" symbol in the text

We note that Barricelli used the "x" symbol in two different ways when discussing symbioorganisms in *Esempi Numerici*. In some places an "x" denotes what he calls the "exclusion sign"

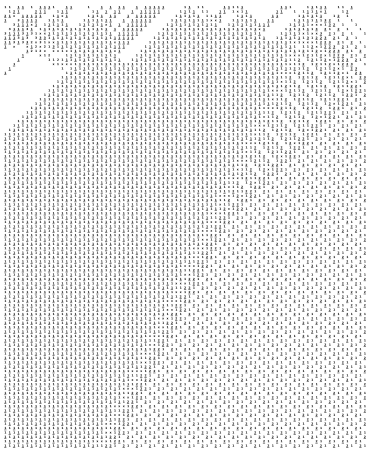
[28]The output of all 100 runs is available in the GitHub repository at https://github.com/tim-taylor/barricelli54/tree/main/output/fig15-100-reruns.

[29]https://github.com/tim-taylor/barricelli54/blob/main/tools/classify-dynamics.py

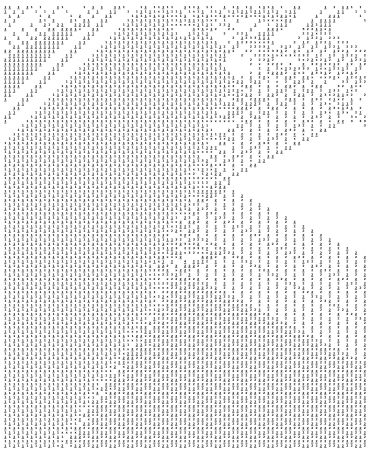
[30]Alternatively, it is possible that he tried multiple initial conditions until he found one with interesting dynamics. However, he does not mention doing this, and it would have required a great deal of time to do so (remembering that the 8,300 numbers in this figure were calculated by hand).



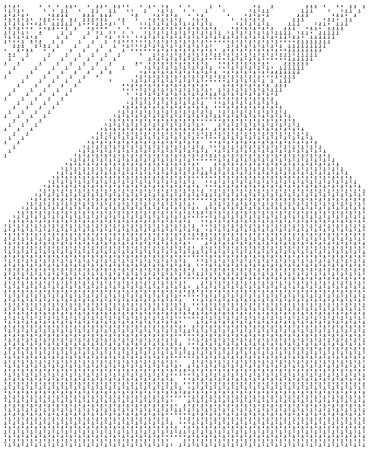
(a) Run 7: Glider



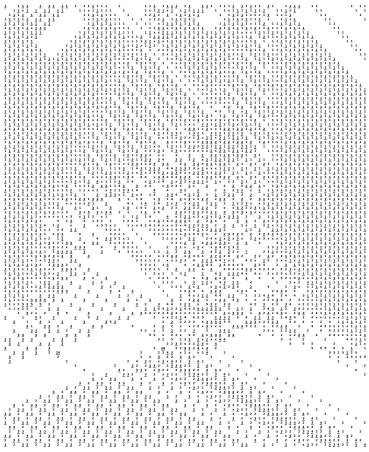
(b) Run 18: Glider



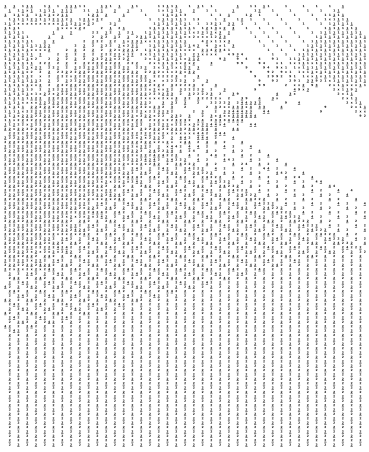
(c) Run 29: Glider



(d) Run 34: Glider



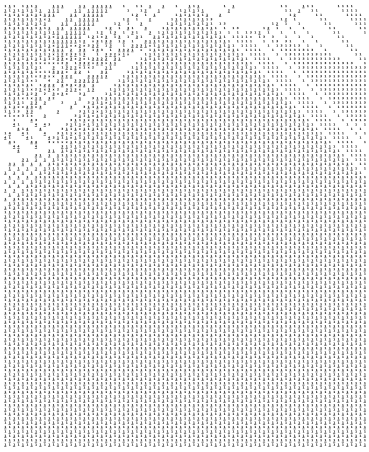
(e) Run 52: Complex



(f) Run 63: Cyclic (length 2)

(g) Run 71: Complex

(h) Run 88: Complex



(i) Run 94: Cyclic (length 2)

Figure 6: Nine randomly chosen outputs from 100 reruns of the configuration that Barricelli used to generate his Figure 15. Each run is categorised as explained in the main text.

that can arise when two or more numbers from one generation are trying to move to the same location in the next generation when the exclusion norm is being used. In other places, when discussing specific symbioorganisms in the text, he uses an "x" to denote an empty cell, e.g. "(5, -3, 1, -3, x, -3, 1, x)".[31]

To avoid confusion, we have used the "□" symbol instead of "x" in the latter case in our translation, so the previous example is written as "(5, -3, 1, -3, □, -3, 1, □)". In later papers Barricelli seems to have recognised this potential for confusion, and likewise switched to using different symbols for denoting empty cells; in (Barricelli, 1959) he uses "s" and in (Barricelli, 1962) he uses "0" for this purpose.

6 Significance and legacy of the work

To the best of our knowledge, Barricelli's *Esempi Numerici* paper presents the first published account of an evolutionary simulation on a computer.[32]

What makes him the earliest pioneer of artificial life experiments in particular, in addition to evolutionary computation, is his focus on natural selection rather than fitness function-guided artificial selection, and on seeking to achieve ongoing, open-ended evolution. Other pioneering aspects of his work include the provisioning of phenotypes ("somatic structures") in his self-reproducing symbioorganisms, in the form of encoded game strategies to be played when the organisms competed against each other;[33] the use of multiple universes running in parallel with occasional exchange of elements between them to guard against homogeneity;[34] and, the suggestion of running evolutionary experiments using real DNA molecules.[35] These aspects of his work should have marked him out as a founding father of the field—if only his work had been more widely known about in the 1980s and early 1990s when the present-day field of Artificial Life was in its infancy. Had more people known about his work then, it would undoubtedly have been influential in defining early research directions in the field.

To put the work in a broader context, the 1954 *Esempi Numerici* paper was published two years before the famous *Dartmouth Summer Research Project on Artificial Intelligence* (the "*Dartmouth workshop*") in 1956, which is commonly regarded as the founding event in the field of artificial intelligence. And in terms of artificial life research, work by other people

[31] On page 52 of the original text this symbioorganism is mistakenly written as "(5,-3,1,3,x,-3,1,x)". The fourth element should be -3, not 3, as shown in Figure 6 of the paper and verified by our own simulations.

[32] David B. Fogel, in his encyclopaedic history of evolutionary computing, agrees with this assessment (D. B. Fogel, 1998, p.163).

[33] This technique of allowing the organism's genome to encode strategies to perform specific tasks in addition to reproduction is now used in the popular Artificial Life platform *Avida* (Ofria et al., 2009).

[34] This technique is now widely used in the evolutionary computing community under the general name of "island models." Perhaps the first discussion of this idea in that community was a technical report by John Grefenstette (1981). As it happens, Grefenstette was at Vanderbilt University at the time, where Barricelli had worked 20 years earlier.

[35] This technique became widely used in the 1990s in the field of DNA computing (Xu et al., 2025).

on self-reproducing digital organisms and open-ended evolution would not surface until the 1960s (most notably with work by Fred Stahl and by Victor Vyssotsky and colleagues (Taylor, 2024)).

In the 650+ pages of the proceedings of the inaugural 1987 workshop on Artificial Life, Barricelli's work is only cited twice, both times in Chris Langton's annotated bibliography of the field included at the end of the volume. The first citation is to the two-part paper in *Acta Biotheoretica* in 1962-1963, with the one-sentence description "An early computer model of evolution featuring a cellular automaton" (Langton, 1989, p.571). The second is to the Reed, Toombs and Barricelli paper, but the stated authorship of the paper is garbled—it actually appears twice in the list, once under the sole authorship of Reed (Langton, 1989, p.609) and again under the dual authorship of Toombs and Barricelli (Langton, 1989, p.618). Langton recently explained that "it was almost certainly either Arthur Burks or John Holland" who had originally told him about Barricelli's work in the 1980s, and that he "knew enough of [Barricelli's] work by reputation to include it in the Bibliography." However, he had not managed to get a copy of any of Barricelli's papers by the time he was preparing the bibliography and therefore missed the significance of Barricelli's contributions (Langton, 2026).

In the proceedings of the second workshop on Artificial Life, which took place in 1990, Barricelli's work is cited once, in Alvy Ray Smith's paper about simple, non-trivial self-reproducing machines in cellular automata (Smith, 1992). Smith, who co-founded groundbreaking computer animation studio Pixar, later stated that Barricelli had influenced his earliest thinking about the possibilities for computer animation and the relationship between life and computation (Hackett, 2014).

However, Smith would remain a rare example of someone from a computer science background recognising Barricelli's contributions, at least until Barricelli's work began to become known a little more widely in the late 1990s onwards.[36]

The paper by Reed, Toombs and Barricelli (1967) was more closely related to evolutionary computing than to artificial life. It too failed to be widely recognised in the early years, although that has improved from the 2000s onwards. David Fogel, in his history of evolutionary computing, describes it as "a truly remarkable contribution ... In retrospect, the paper could have had a profound effect on the course of experimentation in evolutionary computation had it received greater attention" (D. B. Fogel, 1998, p. 361).

The isolation of Barricelli's work from other early developments in artificial life and evolutionary computing was not a one-way street—in addition to other researchers being unaware of his work, Barricelli himself seldom discussed or cited work by others in these areas, even in later years when these fields were becoming well-established. Indeed, with the exception of the paper co-authored with Reed and Toombs, across all of his publications Barricelli

[36] Significant efforts to disseminate Barricelli's work in the late 1990s and thereafter include George Dyson's books *Darwin Among the Machines* (1997) and *Turing's Cathedral* (2012), David B. Fogel's (1998) book *Evolutionary Computation: The Fossil Record*, as well as contributions such as (Galloway, 2011, 2012) and (Taylor & Dorin, 2020).

only ever cited a single paper by other authors in these fields. This was in his final substantive (but unpublished) writing on the topic (Barricelli, 1987), which cited L. J. Fogel et al. (1966)—a work that was over twenty years old at the time. Throughout his career Barricelli associated more with evolutionary biologists than with computer scientists, and participated in various major conferences on genetics and evolution attended by eminent researchers in those fields.[37]

We have not found any reliable information about Barricelli's personal or professional relationship with von Neumann after he arrived at IAS in 1953.[38] It is notable that, despite von Neumann's hopes for a fruitful collaboration as expressed in his letters of support for Barricelli's visits (section 2.3), we have found no record of any specific intellectual exchange between the two. Having said that, the fact that Barricelli was accepted for two return visits to IAS in 1954 and 1956 strongly suggests that von Neumann continued to see value in Barricelli's research. It must also be remembered that von Neumann was diagnosed with cancer in 1955 and died in February 1957.

Opinions of Barricelli's work by his contemporaries were a little mixed. References by colleagues at the University of Oslo in support of his first application to IAS describe him as "industrious and interested" (Barricelli, n.d.-b, p.16) and "able and sincere" (Barricelli, n.d.-a, p.16). Ragnar Frisch, in a letter to von Neumann in 1952, while a little critical of Barricelli's methods, was generally supportive too: "I hope that you will be finding Mr. Barricelli an interesting person to talk with. He is not very systematic always in his exposition, but he does have interesting ideas" (Barricelli, n.d.-b, p.13). Simen Gaure, who worked with Barricelli as a research assistant in Oslo in the early 1980s, offered the following assessment of his approach: "[Barricelli] balanced on a thin line between being truly original and being a crank. ... The scientific community needs a couple of Barricellis each century" (Dyson, 1997, p.129).

Taking a step back from the opinions of some of Barricelli's contemporaries, from today's perspective we can more easily appreciate the pioneering aspects of his achievements in Artificial Life.

Barricelli's work during his first visit to IAS in 1953 took the conceptually novel step of treating the computer not as a calculator but as a substrate for evolutionary dynamics and symbiogenesis. Furthermore, having taken this step, he introduced the idea of digital organisms and ecosystems, and identified open-ended evolution as a topic that could be investigated experimentally. His argument that open-ended evolution requires something more that Darwin's principles is an insight that still resonates with Artificial Life researchers today. *Esempi*

[37] For example, Barricelli presented his work at the Ninth International Congress on Genetics, Bellagio, organised by R. B. Goldschmidt, R. A. Fisher and others in 1953 (see section 2.5) and actively participated in discussion sessions at the *Symposium on Mathematical Challenges to the Neo-Darwinian Interpretation of Evolution* (the "*Wistar Conference*") at the Wistar Institute of Anatomy and Biology, Philadelphia in 1966, chaired by Nobel Laureate Peter Medawar (Moorehead & Kaplan, 1967).

[38] A little more is known about Barricelli's interactions with von Neumann's IAS colleague Albert Einstein. Being two of the minority of staff who did not own a car, it is said that Barricelli and Einstein often shared a bus into work (I. Aars, n.d.; Brahde, 2025) and would discuss relativity and other ideas (Ø. Aars, 1993).

Numerici was the first published paper to describe examples of the emergence and evolution of digital organisms in a computational universe. Barricelli was a pioneer of Artificial Life research over 30 years before the field coalesced into a recognised discipline.

It is our hope that by providing an English translation of the paper, Barricelli's groundbreaking early work in Artificial Life can reach a wider audience and that his pioneering spirit and remarkable achievements can be more easily recognised and appreciated.

Acknowledgements

We gratefully acknowledge and thank the following people (listed in alphabetical order) for their invaluable and generous help in the research and preparation of this commentary:

Ivar Aars; Cato Brahde; Lisa Cool and other staff at Durham University Library, UK; Massimo Curatella; George Dyson; Brynna Farris-McManus (Public Services Archivist) at Vanderbilt University, TN; Alexander Galloway; Richard Goodman; Suzanne Harkins, Linda Lussier and other staff at the University of Aberdeen Library, UK; Chris Langton; Josh Malamy (Department of Genome Sciences) and Joyce Antonio (Department of Biology) at the University of Washington, WA; Luca Manzoni; Barry McMullin; Melissa Mead (University Archivist) and Brenna Rybak (Department of Biology) at the University of Rochester, NY; Stefano Nichele; Massimo Passamonti; Lalaina Rahobisoa; and, Caitlin Rizzo and other staff at the IAS Archives in Princeton, NJ.

References

Aars, I. (n.d.). Nils Aall Barricelli (24. januar 1912 –26. januar 1993) [Recollections and bibliography (in Norwegian) written by Barricelli's half-nephew, provided to TT by Cato Brahde].

Aars, Ø. (1993). Nils Aall Barricelli [Obituary published on 8 February 1993]. *Aftenposten*.

Agazzi, E. (1972). Recent developments of the philosophy of science in Italy. *Zeitschrift für Allgemeine Wissenschaftstheorie*, *3*, 359–371. https://doi.org/10.1007/BF01800759

Barricelli, N. A. (n.d.-a). Director's Office: Member files, Nils Aall Barricelli. From the Shelby White and Leon Levy Archives Center, Institute for Advanced Study, Princeton, NJ, USA. [https://albert.ias.edu/20.500.12111/8340].

Barricelli, N. A. (n.d.-b). School of Mathematics: Member files, Nils Aall Barricelli. From the Shelby White and Leon Levy Archives Center, Institute for Advanced Study, Princeton, NJ, USA. [https://albert.ias.edu/20.500.12111/8675].

Barricelli, N. A. (1947). *The hypothesis on the gene-symbiosis and its importance in the explanation of the origin of the gamic reproduction*. Cammermeyers Boghandel.

Barricelli, N. A. (1953). *Experiments in bionumeric evolution executed by the electronic computer at Princeton, NJ* (tech. rep.) (IAS Archives identifier: ECP-45/3167/Barricelli). Institute for Advanced Study, Princeton, NJ, USA.

Barricelli, N. A. (1954). Esempi numerici di processi di evoluzione. *Methodos*, *6*, 45–68.

Barricelli, N. A. (1955). 5400 generazioni. *Civiltà Delle Macchine*, *3*(3), 25–31.

Barricelli, N. A. (1956). Symbiogenetic evolution processes realized by artificial methods [part 1]. *Methodos*, *8*(32), 305–312.

Barricelli, N. A. (1957). Symbiogenetic evolution processes realized by artificial methods. *Methodos*, *9*(35-36), 143–181.

Barricelli, N. A. (1959, May). *Theory testing by numerical evolution experiments* (tech. rep.). Vanderbilt University.

Barricelli, N. A. (1962). Numerical testing of evolution theories. Part I. Theroetical introduction and basic tests. *Acta Biotheoretica*, *16*(1-2), 69–98. https://doi.org/10.1007/BF01556771

Barricelli, N. A. (1963). Numerical testing of evolution theories. Part II. Preliminary tests of performance. Symbiogenesis and terrestrial life. *Acta Biotheoretica*, *16*(3-4), 99–126. https://doi.org/10.1007/BF01556602

Barricelli, N. A. (1972). Numerical testing of evolution theories. *Journal of Statistical Computation and Simulation*, *1*(2), 97–127. https://doi.org/10.1080/00949657208810008

Barricelli, N. A. (1985). Letter from Nils Aall Barricelli to Sydney Brenner, 8/6/1985 [Cold Spring Harbor Laboratory Archives. Box: CP01, Folder: 36. Identifier: SB_01_01_-0035_143]. https://archivesspace.cshl.edu/repositories/2/archival_objects/52069

Barricelli, N. A. (1987). Suggestions for the starting of numeric evolution processes to evolve symbioorganisms capable of developing a language and technology of their own. *Theoretic Papers*, *6*(6), 119–146.

Barricelli, N. A. (1991). Symbiogenesis theory. *Theoretic Papers*, *12*(6), 61–101.

Barricelli, N. A., Bianchi, G., & Taylor, T. (2026). Numerical examples of evolutionary processes [English translation of "Esempi numerici di processi di evoluzione" (1954)]. *Artificial Life*, *32*(3), 299–317. https://doi.org/10.1162/ARTL.a.485

Barricelli, N. A., Nelson, L., & Toombs, R. (1971). Virus-genetic theory testing by data processing machines I. Basic procedures and models tested. *Journal of Theoretical Biology*, *32*(3), 559–580. https://doi.org/10.1016/0022-5193(71)90156-1

Barricelli, N. A., & Toombs, R. (1971a). Virus-genetic theory testing by data processing machines II. Fit of classical genetic T4 data. *Journal of Theoretical Biology*, *32*(3), 581–601. https://doi.org/10.1016/0022-5193(71)90157-3

Barricelli, N. A., & Toombs, R. (1971b). Virus-genetic theory testing by data processing machines III. The interpretation of radiation genetic and partial phage experiments in T4. General remarks on the theory-testing results. *Journal of Theoretical Biology*, *32*(3), 603–623. https://doi.org/10.1016/0022-5193(71)90158-5

Beach, L. B. (1958, November). Letter from Leonard B. Beach, dean of the Graduate School, Vanderbilt University to Nils Aall Barricelli, dated 21 November 1958 [Special Collections and University Archives, Vanderbilt University].

Bell, A. G. (1978). *The machine plays chess?* Pergamon Press.

Berntsen, D. (2003). A pioneer era in Norwegian scientific computing (1948–1962). In J. Bubenko, Jr., J. Impagliazzo, & A. Sølvberg (Eds.), *History of Nordic computing* (pp. 23–32). Springer. https://doi.org/10.1007/0-387-24168-X_3

Brahde, C. (2025, June). Personal telephone communication with TT.

Dyson, G. (1997). *Darwin among the machines*. Basic Books.

Dyson, G. (2012). *Turing's cathedral: The origins of the digital universe*. Vintage Books.

Fisher, R. A. (1930). *The genetical theory of natural selection*. Oxford University Press.

Fogel, D. B. (1998). *Evolutionary computation: The fossil record*. IEEE Press.

Fogel, D. B. (2006). Nils Barricelli—artificial life, coevolution, self-adaptation. *IEEE Computational Intelligence Magazine*, (February), 41–45. https://doi.org/10.1109/MCI.2006.1597062

Fogel, L. J., Owens, A. J., & Walsh, M. J. (1966). *Artificial intelligence through simulated evolution*. John Wiley & Sons.

Fondazione Ansaldo. (n.d.). Machine Civilization [Last accessed 5 May 2026]. https://www.fondazioneansaldo.it/index.php/archimondi-archivio/621-civilta-delle-macchine

Galloway, A. R. (2011). Creative evolution. *Cabinet*, (42), 45–50. https://www.cabinetmagazine.org/issues/42/galloway.php

Galloway, A. R. (2012). The computational image of organization: Nils Aall Barricelli. *Grey Room*, *46*(Winter), 26–45. https://doi.org/10.1162/GREY_a_00059

Gardner, M. (1958). Mathematical games: Concerning the game of nim and its mathematical analysis. *Scientific American*, *198*(2), 104–111.

Gilchrist, B. (2006). Remembering some early computers, 1948–1960 [Last accessed 5 May 2026]. https://www.columbia.edu/cu/computinghistory/gilchristearlycomputers.pdf

Goodman, R. E. (2012). Recollections of Nils Aall Barricelli [Unpublished memoire, dated 27 February 2012. Personal communication with TT, 24 June 2014].

Grefenstette, J. J. (1981). *Parallel adaptive algorithms for function optimization* (tech. rep.) (No. CS-81-19). Computer Science Department, Vanderbilt University. Nashville, TN.

Gulliksen, T. (1993). Nils Aall Barricelli [Obituary released by the Institute of Mathematics, University of Oslo, 8 February 1993].

Hackett, R. (2014). Meet the father of digital life. *Nautilus*, (14). https://nautil.us/meet-the-father-of-digital-life-234937

Haldane, J. B. S. (1924). A mathematical theory of natural and artificial selection, Part I. *Transactions of the Cambridge Philosophical Society*, *23*(2), 19–41.

Hayes, J. E., & Levy, D. N. L. (1976). *The world computer chess championship, Stockholm 1974*. Edinburgh University Press.

Kozo-Polyansky, B. (1924, August). *Novyi printzip biologii. Ocherk teorii simbiogeneza*. Puchina.

Kozo-Polyansky, B. (2010). *The new principle of biology: An essay on the theory of symbiogenesis* (V. Fet & L. Margulis, Eds.) [Translated from the Russian by Victor Fet]. Harvard University Press.

Langton, C. G. (Ed.). (1989). *Artificial life: Proceedings of an interdisciplinary workshop on the synthesis and simulation of living systems held September, 1987 in Los Alamos, New Mexico*. Addison-Wesley Publishing Co.

Langton, C. G. (2026, February). Personal email communication with TT.

Lewontin, R. C. (1970). The units of selection. *Annual Review of Ecology and Systematics*, *1*, 1–18. https://doi.org/10.1146/annurev.es.01.110170.000245

Montalenti, G., & Chiarugi, A. (Eds.). (1953). *Proceedings of the 9th international congress of genetics* (Vol. 6 (suppl.)). Caryologia.

Moorehead, P. S., & Kaplan, M. M. (Eds.). (1967). *Mathematical challenges to the neo-Darwinian interpretation of evolution*. Wistar Institute Press.

Ofria, C., Bryson, D. M., & Wilke, C. O. (2009). Avida: A software platform for research in computational evolutionary biology. In M. Komosinski & A. Adamatzky (Eds.), *Artificial life models in software* (pp. 3–35). Springer. https://doi.org/10.1007/978-1-84882-285-6_1

Passamonti, M. (2026, May). Personal email communication with TT.

Rahobisoa, L. (2011). *Internship report: From 4th July 2011 to 19th August 2011* [Supervisor: Barry McMullin], The RINCE Institute, Dublin City University.

Reed, J., Toombs, R., & Barricelli, N. A. (1967). Simulation of biological evolution and machine learning: I. Selection of self-reproducing numeric patterns by data processing machines, effects of hereditary control, mutation type and crossing. *Journal of Theoretical Biology*, *17*(3), 319–342. https://doi.org/10.1016/0022-5193(67)90097-5

Rutherford Laboratory Bulletin. (1963). Bulletin no. 103, 7 January 1963 [https://www.chilton-computing.org.uk/ChiltonCatalog/rutherford-laboratory-bulletin/1963.103-109-rutherford-laboratory-bulletin.pdf].

Singleton, W. R. (1954). IX International Genetics Congress. *A.I.B.S. Bulletin*.

Smith, A. R. (1992). Simple non-trivial self-reproducing machines. In C. G. Langton, C. Taylor, J. D. Farmer, & S. Rasmussen (Eds.), *Artificial life II: Proceedings of the workshop on artificial life, held February 1990 in Santa Fe, New Mexico* (pp. 709–725). Addison-Wesley Publishing Co.

Stadler, D. (1992). Herschel Roman and 50 years of genetics at the University of Washington [Transcript of Genetics Department seminar presented on 14 December 1992. https://www.gs.washington.edu/about/history/a-history-of-the-department-of-genome-sciences/herschel-roman-and-50-years-of-genetics-at-the-university-of-washington/. Last accessed 11 September 2026].

Stahl, F. (2007). Interview with Frank Stahl (University of Oregon) by George Dyson [Transcript provided to TT by George Dyson].

Taylor, T. (2024). An afterword to "Rise of the Self-Replicators": Placing John A. Etzler, Frigyes Karinthy, Fred Stahl, and others in the early history of thought about self-reproducing machines. *Artificial Life*, *30*(1), 91–105. https://doi.org/10.1162/artl_a_00424

Taylor, T. (2025). barricelli54 [Code repository: C++ reimplementation of Barricelli's 1954 simulations]. https://github.com/tim-taylor/barricelli54

Taylor, T., & Dorin, A. (2020). *Rise of the self-replicators: Early visions of machines, AI and robots that can reproduce and evolve* [https://www.tim-taylor.com/selfrepbook/]. Springer. https://doi.org/10.1007/978-3-030-48234-3

The Econometric Society. (n.d.). In memory of fellows of the Econometric Society [Last accessed 5 May 2026]. https://www.econometricsociety.org/society/organization-and-governance/fellows/memoriam

The Staff, Electronic Computer Project. (1954). *Final report on contract no. DA-36-034-ORD-1023* (tech. rep.) (This report also appeared in identical form under the title "Report on Contract No. N-7-ONR-388 T.O. 1"). Institute for Advanced Study, Princeton, NJ, USA. https://albert.ias.edu/20.500.12111/9735

Tinbergen, J. (1974). Ragnar Frisch's role in econometrics: A sketch. *European Economic Review*, *5*(1), 3–6. https://doi.org/10.1016/0014-2921(74)90003-8

University of Oslo. (2024). Department of Mathematics: New course in the 1950s [Article published online by the university's Museum of University and Science History. Last modified 3 December 2024]. https://www.muv.uio.no/uios-historie/fag/matematikk-naturvitenskap/matematikk/matematikk-60tall-nvjohansen.html

University of Rochester. (n.d.). Terminated faculty files: Nils Aall Barricelli [The University of Rochester Archives, Department of Rare Books, Special Collections, and Preservation. Various documents with dates from 3 February 1956 to 7 August 1957].

von Neumann, J., & Morgenstern, O. (1944). *Theory of games and economic behavior*. Princeton University Press.

Xu, H., Yu, Y., Li, P., Liu, S., Yan, X., Zhou, Z., & Tian, Y. (2025). DNA computing: DNA circuits and data storage. *Nanoscale Horizons*, *10*(3204). https://doi.org/10.1039/d5nh00459d